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THE ONE-SAMPLE K-S TEST: TI-59 PROGRAMS FOR DISCRETE AND CONTIN--ETC(U)
MAR 81 D W BROWN

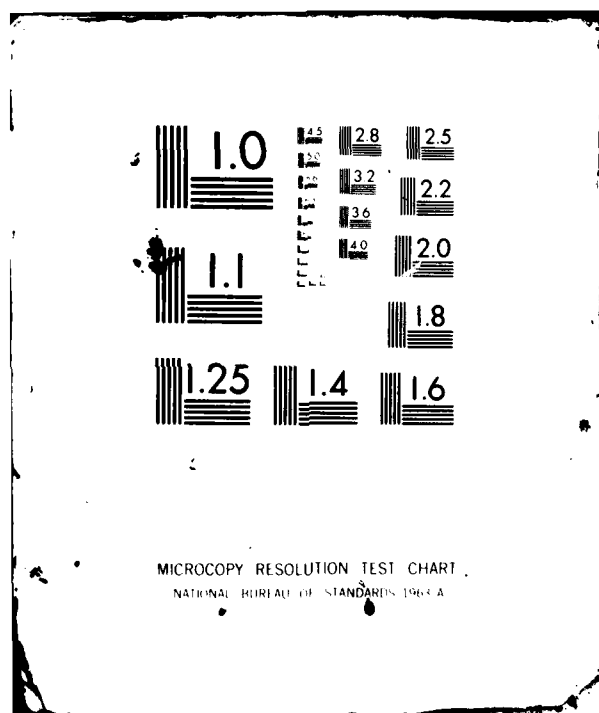
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THESIS

THE ONE-SAMPLE K-S TEST: TI-59 PROGRAMS
FOR DISCRETE AND CONTINUOUS RANDOM VARIABLES

by

Douglas Warren Brown

March 1981

Thesis Advisor:

D.R. Barr

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The One-Sample K-S Test: TI-59 Programs
for Discrete and Continuous Random Variables

by

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

The Kolmogorov-Smirnov (K-S) goodness-of-fit test is a nonparametric test if the random variable is continuous. If the random variable is discrete the K-S test is not nonparametric.

Two programs for the TI-59 programmable calculator are presented, "Continuous K-S" and "Discrete K-S". They are designed to conduct a K-S test and display the significance level. User instructions and several sample problems are presented.

Use of the "hidden registers" in the TI-59 is discussed. The hidden registers are used extensively in the program Discrete K-S.

TABLE OF CONTENTS

I.	INTRODUCTION -----	6
II.	THE KOLMOGOPOV-SMIRNOV (K-S) TEST -----	7
III.	TRANSFORMATIONS OF SAMPLE DATA -----	15
IV.	THE K-S TEST: CONTINUOUS RANDOM VARIABLE -----	17
	A. DISTRIBUTIONS OF THE TEST STATISTICS -----	17
	B. USER INSTRUCTIONS FOR "CONTINUOUS K-S" -----	18
	C. USER INSTRUCTIONS TO EVALUATE A GIVEN TEST STATISTIC -----	24
V.	THE K-S TEST: DISCRETE RANDOM VARIABLE -----	25
	A. DISTRIBUTIONS OF THE TEST STATISTICS -----	25
	B. USER INSTRUCTIONS FOR "DISCRETE K-S" -----	27
APPENDIX A	CONTINUOUS K-S: ENTRY PROCEDURE, PROGRAM LISTING, AND EXAMPLES -----	32
APPENDIX B	DISCRETE K-S: ENTRY PROCEDURE, PROGRAM LISTING, AND EXAMPLES -----	50
APPENDIX C	CONDENSED USER INSTRUCTIONS FOR CONTINUOUS K-S AND DISCRETE K-S -----	65
APPENDIX D	USE OF PENDING ARITHMETIC REGISTERS IN THE TI-59 -----	68
	LIST OF REFERENCES -----	71
	INITIAL DISTRIBUTION LIST -----	72

I. INTRODUCTION

The subject of this thesis is the one-sample Kolmogorov-Smirnov (K-S) goodness-of-fit test. The purpose of the thesis is to provide the reader with programs enabling him to perform K-S tests on the TI-59 programmable calculator.

The distinction between continuous and discrete random variables is a central issue. Different computational procedures are appropriate when testing a discrete random variable than when testing a continuous random variable. Two separate TI-59 programs are provided: "Continuous K-S" and "Discrete K-S".

Section II is a general discussion of the K-S test. Section III explains the technique of transforming sample data before performing a K-S test. Section IV discusses the distribution of test statistics from a continuous K-S test and provides detailed instructions on how to use the Continuous K-S program. Section V is an analagous discussion for a discrete K-S test.

Appendices A and B are entry instructions, program listings, and example problems for Continuous K-S and Discrete K-S, respectively. Appendix C presents condensed user instructions for both programs. Appendix D discusses the use of the "hidden registers" in the TI-59.

II. THE KOLMOGOROV-SMIRNOV (K-S) TEST

A. OVERVIEW OF THE K-S TEST

Statisticians are often faced with observations of a random variable based on a population with an unknown probability distribution. A goodness-of-fit test may be used to test certain hypotheses about the relationship between the population's distribution and some specified distribution. The one-sample Kolmogorov-Smirnov (K-S) test is a goodness-of-fit test. The term "one-sample" is used because a "two-sample" K-S test has also been developed. The two-sample test examines the relationship between two unknown probability distributions on the basis of two random samples from different populations. Only the one-sample K-S test is discussed herein. It will be referred to below as simply the "K-S test".

The K-S test is conducted by comparing S_n , the empirical cumulative distribution function (CDF), defined below, with H , the hypothesized CDF. If the discrepancy between S_n and H , called the "test statistic", is large then we have strong evidence that F , the population CDF, does not equal H . The probability of observing a test statistic at least as large as that realized is called the "significance level" of the test.

A K-S test is only valid if outcomes on the random variable lie on an ordinal scale. If a random variable maps events into cells between which no ordinal relationship exists then the chi square goodness-of-fit test is recommended [Ref. 1: pp. 237].

Any goodness-of-fit test can be either a hypothesis test or a significance test. For a hypothesis test we specify a null hypothesis, H_0 , an alternative hypothesis, H_1 , and an "alpha level". After we compute the significance level we compare it with the alpha level. If the significance level is less than or equal to the alpha level then we reject H_0 and accept H_1 . Otherwise, we do not reject H_0 . To conduct a significance test we simply compute the significance level; we are not formally concerned about rejecting H_0 .

The requisite computational techniques, yet to be discussed, are identical for hypothesis and significance testing. For either type of test the test statistic must be computed and then evaluated by computing the significance level. Hence, the discussion of the K-S test below will focus on those two steps.

Let X_1, X_2, \dots, X_n be independent observations on the random variable X which has CDF F . Assume an ordinal relationship exists between all possible values of X . If $X_{(1)}, X_{(2)}, \dots, X_{(n)}$ represent the n observations arranged in ascending order then the empirical CDF, S_n is defined as:

$$S_n(x) = \begin{cases} 0 & \text{if } x < X_{(1)} \\ k/n & \text{if } X_{(k)} \leq x < X_{(k+1)}, \quad k = 1, 2, \dots, n-1 \\ 1 & \text{if } x \geq X_{(n)} \end{cases}$$

The K-S test may be used to test the following three pairs of hypotheses given a specified CDF H . The appropriate test statistic is also listed.

1. $H_0: F(x) \geq H(x) \text{ for all } x$

$H_1: F(x) < H(x) \text{ for some } x$

Test statistic: $D^- = \sup_x (H(x) - S_n(x))$

2. $H_0: F(x) \leq H(x) \text{ for all } x$

$H_1: F(x) > H(x) \text{ for some } x$

Test statistic: $D^+ = \sup_x (S_n(x) - H(x))$

3. $H_0: F(x) = H(x) \text{ for all } x$

$H_1: F(x) \neq H(x) \text{ for some } x$

Test statistic: $D = \max(D^-, D^+)$

Note that by simply specifying H_0 we implicitly specify H_1 since H_1 is the negation of H_0 . It should also be noted that the first two null hypotheses listed pertain to what is commonly called "one-sided" tests while the third pertains to a "two-sided" test. The test statistics, D^- , D^+ , and D , are collectively called the "K-S statistics".

B. CALCULATING THE VALUE OF THE TEST STATISTIC

1. Discrete Random Variable

When examining a discrete random variable the the test statistics D^- and D^+ are found by comparing the

empirical and hypothesized CDFs at each possible value of the random variable. More precisely,

$$D^+ = \max \{0, \max[S_n(x) - H(x)]\}$$

and
$$D^- = \max \{0, \max[H(x) - S_n(x)]\}.$$

Figure 1 illustrates this approach.

2. Continuous Random Variable

If we are examining a continuous random variable we calculate D^+ and D^- using the values of the empirical and hypothesized CDFs at the observed values in our sample. The computation of D^+ is analogous to the procedure used with a discrete random variable. The computation of D^- , however, is conceptually different. Using previous notation:

$$D^+ = \max\{0, \max[S_n(X_{(i)}) - H(X_{(i)})]\}, \quad i = 1, 2, \dots, n$$

$$D^- = \max\{0, \max[H(X_{(i)}) - S_n(X_{(i-1)})]\}, \quad i = 1, 2, \dots, n$$

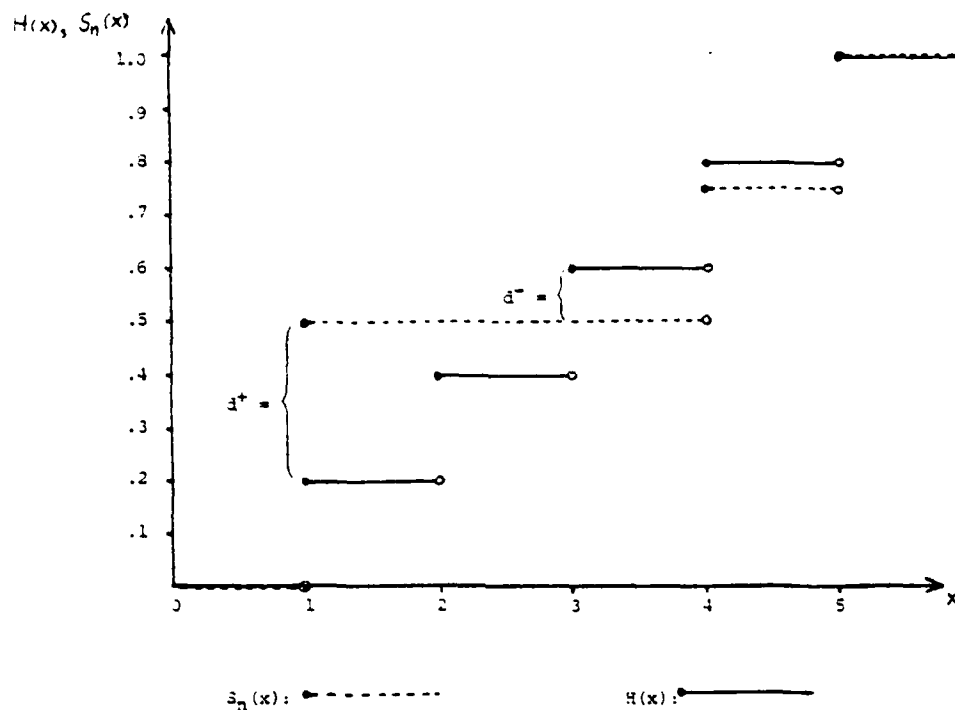
We define $X_{(0)} = -\infty$, thus $S_n(X_{(0)}) = 0$. Figure 2 illustrates this approach.

C. HISTORICAL ORIGINS OF THE K-S TEST

The K-S test was first introduced by Kolmogorov in 1933 [Ref. 2] and was further developed by Smirnov [Ref. 3]. The essence of the original work in this field was the derivation of the distribution of the K-S statistics D^+ , D^- , and D . Continuity of the random variable was a key assumption in the development of the test. The statistics D^+ and D^- were discovered to follow the same distribution and this distribution was derived exactly. The distribution

Hypothesized distribution: $H(x) = x/5$, $x = 1, 2, 3, 4, 5$

Sample data: 1, 1, 4, 5 (sample size $n = 4$)



$$\begin{aligned}
 d^+ &= \max\{0, \max_x [S_n(x) - H(x)]\}, x = 1, 2, 3, 4, 5 \\
 &= \max\{0, \max[(.5-.2), (.5-.4), (.5-.6), (.75-.8), (1-1)]\} \\
 &= \max\{0, \max[.3, .1, -.1, -.05, 0]\} \\
 &= .3
 \end{aligned}$$

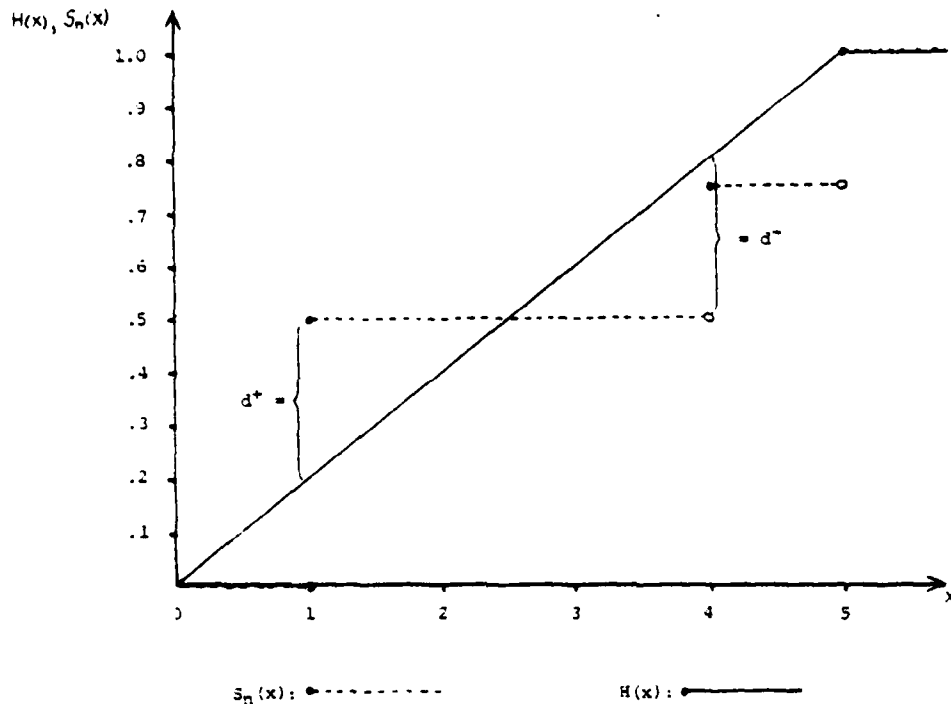
$$\begin{aligned}
 d^- &= \max\{0, \max_x [H(x) - S_n(x)]\}, x = 1, 2, 3, 4, 5 \\
 &= \max\{0, \max[(.2-.5), (.4-.5), (.6-.5), (.8-.75), (1-1)]\} \\
 &= \max\{0, \max[.3, .1, .1, .05, 0]\} \\
 &= .1
 \end{aligned}$$

Figure 1

Example: Test Statistics from a Discrete K-S

Hypothesized distribution: $H(x) = \begin{cases} 0 & ; x < 0 \\ x/5 & ; 0 \leq x \leq 5 \\ 1 & ; x > 5 \end{cases}$

Sample data: 1, 1, 4, 5 (ties occur from rounding error)



$$\begin{aligned} d^+ &= \max \{0, \max_{i=1}^4 [S_n(x_{(i)}) - H(x_{(i)})]\} , i = 1, 2, 3, 4 \\ &= \max\{0, \max[(.5-.2), (.5-.2), (.75-.8), (1-1)]\} \\ &= \max\{0, \max[.3, .3, -.05, 0]\} \\ &= .3 \end{aligned}$$

$$\begin{aligned} d^- &= \max\{0, \max_{i=1}^4 [H(x_{(i)}) - S(x_{(i-1)})]\} , i = 1, 2, 3, 4 \\ &= \max\{0, \max[(.2-0), (.2-.5), (.8-.5), (1-.75)]\} \\ &= \max\{0, \max[.2, -.3, .3, .25]\} \\ &= .3 \end{aligned}$$

note: by definition, $x_{(\phi)} = -\infty$, thus, $S_n(x_{(\phi)}) = 0$

Figure 2

Example: Test Statistics from a Continuous K-S

of D was closely approximated. The accuracy of the approximation was shown to be very high when the significance level of a test is small. Bradley [Ref. 4: pp. 296] has presented a derivation of the distribution of the K-S statistics which is based upon, but more readable than, the original arguments.

When the hypothesized distribution, H , equals the true distribution, F , and the random variable is continuous then the distributions of the K-S statistics have been shown to be independent of H . For this reason the continuous K-S test is a "nonparametric" test. Tables are widely available, e.g., Bradley [Ref. 4: pp. 367], delineating the distribution of the K-S statistics as a function only of sample size. This is done by showing the "critical values" of the test statistics for certain widely used alpha levels. The user is thus relieved of having to compute the significance level when performing a hypothesis test. He need only compute the test statistic and compare it to the critical value.

It is incorrect to consider the K-S test to be a nonparametric test when the random variable of interest is discrete. Conover [Ref. 5] has shown how the distributions of the K-S statistics for a discrete random variable are dependent upon both the particular hypothesized distribution and the sample size. If the K-S statistics which result from testing a discrete random variable are assumed to follow the

distributions derived by Kolmogorov then the significance level computed will be larger than the true significance level. Similarly, reliance on tables such as Bradley's will impose critical values that are unnecessarily large for a given alpha level. By either relying directly upon Kolmogorov's distributions or upon tables such as Bradley's the effect is the same. The evidence against H_0 , the null hypothesis, will appear much weaker (or "less significant") than it really is.

III. TRANSFORMATION OF SAMPLE DATA

The K-S test is usually applied without employing transformations on the sample data. However, since it is sometimes convenient to transform data before conducting a K-S test, the Continuous K-S program is designed to utilize transformations as a user option. Transformations are not recommended for a discrete K-S test.

Assume W is a continuous random variable with CDF H and a transformation M is defined such that $M(W)$ has a known CDF, G . Further assume that we have observations on a continuous random variable X with some unknown CDF, F . We may conduct a K-S test of our hypothesis concerning the relationship between F and H in two ways. Without using any transformation the empirical CDF S_n may be compared to H . Alternatively, the empirical CDF S_n' may be compared to G , where S_n' is based upon observations of the random variable $M(X)$. Both methods will yield the same test statistic and significance level.

A frequent use of this technique is to define the transformation M to be the function H , i.e., to invoke the probability integral transformation [Ref. 6: pp. 202]. For instance, given a continuous random variable X with CDF H the probability integral transformation tells us that the random variable $H(X)$ is distributed uniform $(0,1)$. If X is

the population random variable in a K-S test and H is the hypothesized CDF, we may wish to compare the empirical CDF S_n' from observations on $H(X)$ to a uniform $(0,1)$ CDF. This might be easier than directly comparing S_n to H . Example 3 in Appendix A illustrates this approach.

As another example, it is sometimes convenient to employ a transformation when the hypothesized distribution is lognormal. By definition, the random variable W is distributed lognormal (μ, σ^2) if and only if $\ln(W)$ is distributed normal (μ, σ^2) [Ref. 6: pp. 117]. Thus, if we have observations on a random variable X and we hypothesize that X is distributed lognormal (μ, σ^2) , we may simplify computation by transforming the data. By treating the values of $\ln(x)$ as our sample data and normal (μ, σ^2) as our hypothesized distribution we can take advantage of the normal CDF subroutine in the TI-59 calculator. See example 4 in Appendix A.

IV. THE K-S TEST: CONTINUOUS RANDOM VARIABLE

A. DISTRIBUTIONS OF THE TEST STATISTICS

The test statistic in a K-S test is a random variable with a particular probability distribution. After conducting a K-S test with test statistic T ($T = D^+$, D^- , or D) we observe some value, t , from the distribution of T . To find the test's significance level we compute $P(T \geq t)$. If $T = D^+$ or D^- it was shown by Birnbaum and Tingey [Ref. 7] that

$$(IV.1) \quad P(T \geq t) = t \sum_{j=0}^{[n(1-t)]} \binom{n}{j} (1-t-j/n)^{n-j} (t+j/n)^{j-1}$$

where n is sample size, $\binom{n}{j} = n!/j!(n-j)!$, and $[n(1-t)]$ is the largest integer contained in $n(1-t)$. For $T = D$ the probability value above should be doubled. The significance levels computed with equation IV.1 will be exact for one-sided tests. For a two-sided test the doubled result will be an upper bound on the true significance level. The difference between the upper bound and the exact value will be negligible when $P(D \geq t)$ is small.

For large sample sizes there are useful approximations to equation IV.1, but their accuracies are marginal for sample sizes as small as $n = 50$. On the other hand, the

difficulty in using equation IV.1 for hand computation is considerable for sample sizes greater than $n = 12$. Furthermore, even finding the value of the test statistic can be tedious. The Continuous K-S program implements equation IV.1 using a TI-59 calculator and is listed in Appendix A along with several example problems. The program is designed for sample sizes less than $n = 55$ and is used as follows.

B. USER INSTRUCTIONS FOR "CONTINUOUS K-S" PROGRAM

STEP ONE - Specifying the test: The user must choose which continuous probability distribution, H , will be compared against the empirical distribution from the sample data (or the transformed sample data). The program's options for H are: normal, exponential, Weibull, or uniform. If H is normal then the Applied Statistics module must be used, otherwise, any module may be used in the calculator. The user must specify the appropriate parameter(s) of H .

STEP TWO - Entering the data: Once the test is specified, read both sides of Card 1 (Continuous K-S) into the TI-59. A printer may be used but it is not required. To enter the data (in any order):

Enter	Press	Display	Printer (Optional)
	E	399.69	
X_i ($i = 1, \dots, n$)	A	1	X_i
	C	1	<div style="display: flex; align-items: center;"> <div style="margin-right: 10px;">sorted data</div> <div style="border-left: 1px solid black; padding-left: 10px;"> <div style="text-align: center; margin-bottom: 5px;">"INPUT DATA"</div> $X_{(1)}$ 01 $X_{(2)}$ 02 \vdots \vdots \vdots $X_{(n)}$ n 0 n+1 0 n+2 \vdots \vdots \vdots </div> </div>
			<div style="display: flex; align-items: center;"> <div style="margin-right: 10px;">ignore</div> <div style="border-left: 1px solid black; padding-left: 10px;"> \vdots \vdots \vdots </div> </div>

There will be a delay after pressing "C" while the calculator sorts the data into ascending order. For a sample of size 10 this will take about 1 minute while for the maximum sample size of 54 the sorting requires about 15 minutes. The user may find it preferable to sort the data himself. If the user enters the data in ascending order the delay will be between 10 and 75 seconds after pressing "C", depending upon sample size. If the printer is used a listing of the ordered input data will be produced.

If the sorted data are to be tested directly without the use of a transformation the next step should be omitted.

STEP THREE - Transforming the data: If a transformation is desired the user must provide it as a subroutine for Card 1. The subroutine must begin with "LBL E'" and end with "INV SBR". After Card 1 has been read into the

calculator the user should enter the subroutine, beginning at program step 325. It must not exceed 75 steps in length. For a sample size of size n , the subroutine must use only registers numbered $n+1$ through 57. The subroutine should be written to be called when value X is currently in the "x-register" and $M(X)$, i.e., the transformed value, is to be returned to the main program by the subroutine.

For example, assume a transformation t defined as :

$$M(X) = (X-2)/3 .$$

After reading Card 1 into the calculator the appropriate steps are:

Press	Display
GTO 325	
LRN	325 00
LBL	326 00
E'	327 00
-	328 00
2	329 00
)	330 00
+	331 00
3	332 00
)	333 00
INV SBR	334 00
LRN	

After entering the transformation the user should test it before proceeding. In the above example $M(8) = 2$. To test: enter "8", press "E'", and the calculator should display "2".

After validating the transformation subroutine the user should press "B'". When the transformation is completed $M(X(n))$ is displayed. If a printer is used the transformed

data are listed. The user is now ready to perform the K-S test.

If the hypothesized distribution, H , is lognormal (μ, σ^2) then a different procedure is followed since the appropriate transformation is provided as an optional subroutine on Card 1. After entering the data and pressing "C" the program will sort (or confirm that the user has sorted) the original data. The user then presses "A'". This will transform each observed value of X to $\ln(X)$. The calculator will display $\ln(X_{(n)})$ a few moments later and, if a printer is used, a listing of the transformed data will be produced. The K-S test can then be conducted by comparing the transformed data to a normal (μ, σ^2) distribution.

If H is lognormal then a K-S test can be performed with Continuous K-S only if the sample data is transformed. A lognormal random variable is strictly positive. Hence, if any input values are nonpositive the calculator will flash after "A'" is pressed, indicating an error.

STEP FOUR - Conducting the test: Both sides of Card 2 (Continuous K-S) should be read into the calculator. Card 2 is initialized differently depending on the hypothesis being tested.

a. Initialization:

- (1) press A if $H_0: F(x) = H(x) \text{ for all } x$
 $H_1: F(x) \neq H(x) \text{ for some } x$

- (2) press B if $H_0: F(x) \geq H(x)$ for all x
 $H_1: F(x) < H(x)$ for some x
- (3) press C if $H_0: F(x) \leq H(x)$ for all x
 $H_1: F(x) > H(x)$ for some x

In all cases "0" is displayed. If the user changes his mind about the direction of his hypotheses after initializing he should press "RST" before pressing the correct user label.

b. Defining H and computing significance level (S.I.):

- (1) Normal (μ, σ^2)

Enter	Press	Display
μ	A	μ
σ	R/S	S.I.

- (2) Exponential (λ) { $H(x) = 1 - e^{-\lambda x}$; $x \geq 0$ }

Enter	Press	Display
λ	B	1
1	R/S	S.I.

- (3) Weibull (λ, α) { $H(x) = 1 - e^{-(\lambda x)^\alpha}$; $x \geq 0$ }

Enter	Press	Display
λ	B	1
α	R/S	S.I.

- (4) Uniform (a,b)

Enter	Press	Display
a	C	a
b	R/S	S.I.

The computation time will vary from 1 minute with sample size of 10 up to 20 minutes for the maximum sample size of 54. After the computation is finished and the significance level is displayed the user may recall the test statistic from register 20.

STEP FIVE - Evaluating the significance level:

The significance level computed may be considered exact if conducting a one-sided test. After conducting a two-sided test if the significance level computed is less than .1 it may be considered accurate to 4 decimal places. [Ref. 4: pp. 301] Since most alpha levels are at most .1 it is anticipated that virtually all user requirements will be satisfied with this degree of accuracy.

When the data "agree closely" with the hypothesized distribution then the significance level computed in a two-sided test may be considerably larger than the true value; it may even exceed 1. When this happens the user should conclude that the sample data is consistent with the null hypothesis.

C. USER INSTRUCTIONS TO EVALUATE A GIVEN TEST STATISTIC

If a user already knows the value of the test statistic from a K-S test on a continuous random variable he may use Continuous K-S in the TI-59 to evaluate the significance level. This will provide the user with more precise information than he could get by consulting a table of critical values.

Assume that a K-S test was conducted with sample size n and that the observed value of the test statistic was t . The user should first repartition the calculator by entering "7" and pressing "Op 17". The calculator will display "399.69". Both sides of Card 2 should then be read into the calculator. The significance level (S.L.) of the test may be computed by the following steps:

Enter	Press	Display
n	STO 59	n
t	STO 00	t
	E	S.L.

If the test was one-sided the significance level displayed may be considered exact. If n and t were from a two-sided test the significance level displayed should be doubled. The comments in STEP FIVE of the USER INSTRUCTIONS above apply when using the program to evaluate a known test statistic from a two-sided test.

V. THE K-S TEST: DISCRETE RANDOM VARIABLE

A. THE DISTRIBUTIONS OF TEST STATISTICS

The distributions of the K-S statistics are not independent of the hypothesized distribution, H , when the random variable is discrete. If a test statistic in such a case is evaluated using formula IV. 1 (employed by Continuous K-S) the significance level computed should be viewed as a very conservative upper bound on the true significance level. Conover [Ref. 5] has derived the distribution of the K-S statistics when H is discrete. He has shown that

$$(V.1) \quad P(D^+ \geq t) = \sum_{j=0}^{[n(1-t)]} \binom{n}{j} f_j^{n-j} e_j$$

with notation defined as:

1. $[n(1-t)]$ is the largest integer in $n(1-t)$

$$2. \binom{n}{j} = n! / j!(n-j)!$$

$$3. f_j = P\{X < H^{-1}(1 - t - j/n + \epsilon)\}$$

where X has distribution function H and

$$H^{-1}(p) = \begin{cases} +\infty & , \quad p > 1 \\ \sup \{x; H(x) < p\} & , \quad 0 < p < 1 \\ -\infty & , \quad p < 0 \end{cases}$$

4. $e_0 = 1$ and

$$e_k = 1 - \sum_{j=0}^{k-1} \binom{k}{j} r_j^{k-1} e_j, \quad k \geq 1$$

5. The value "eps" is a positive number that approaches, but does not reach, zero. In the notation of the limit arguments from calculus: $\text{eps} \rightarrow 0^+$.

Similarly,

$$(V.2) \quad P(D^- \geq t) = \sum_{j=0}^{\lfloor n(1-t) \rfloor} \binom{n}{j} c_j^{n-j} b_j$$

with additional notation defined as:

$$1. \quad c_j = P\{X \geq H(t + j/n)\}$$

$$2. \quad b_0 = 1 \text{ and}$$

$$b_k = 1 - \sum_{j=0}^{k-1} \binom{k}{j} c_j^{k-1} b_j, \quad k \geq 1.$$

Finally, for a two-sided test, the distribution of D is closely approximated as follows for small values of t :

$$(V.3.) \quad P(D \geq t) = P(D^+ \geq t) + P(D^- \geq t) - P(D^+ \geq t)P(D^- \geq t)/2$$

with a maximum error term of $P(D^+ \geq t)P(D^- \geq t)/2$. For significance levels less than or equal to .1 the error will be negligible.

B. USER INSTRUCTIONS FOR "DISCRETE K-S" PROGRAM

The equations defined above require an unacceptable amount of effort to employ by hand computation. The Discrete K-S program implements them on the TI-59 calculator and is listed in Appendix B along with several example problems.

STEP ONE - Checking the Problem Size:

Discrete K-S is designed to test a discrete random variable with m possible outcomes. It may be necessary to aggregate possible outcomes into cells since m must be less than 21. With a sample of size n the program can perform a K-S test if $\{[n(1-t)] + m\} \leq 54$. By convention, $[n(1-t)]$ is defined to be the largest integer in $n(1-t)$. Of course, the value of t , the test statistic, is unknown before the test is conducted but if $(n + m) \leq 54$ then the requirement above is certainly met. If $(n + m)$ is only slightly greater than 54 the data should be entered and processed with Card 1 as explained below. The program will compute the value of the test statistic and indicate if the problem is too large to complete.

STEP TWO - Defining the Hypothesized Distribution:

Each possible value of the random variable being investigated must be classified as falling in one of the m cells. The user must specify the hypothesized distribution, H , in terms of the cells. This may be done in one of two

ways. For each cell i the user can specify either n_i or H_i . For a random observation, X , on the random variable we define n_i and H_i as follows:

$$n_i = P(X \text{ is in cell } i) , \quad i = 1, 2, \dots, m$$

$$H_i = P(X \text{ is in cell } j ; j \leq i) , \quad i = 1, 2, \dots, m$$

We call n_i the mass value of cell i and H_i the cumulative mass value of cell i . The number of the n sample observations that fall into cell i is denoted X_i .

STEP THREE - Initializing the Program and Entering the Data:

Read both sides of Card 1 (Discrete X-S) into the calculator and proceed as follows.

Enter	Press	Display
	E	0
(if H defined by n_i 's)		
	E'	0
(if H defined by H_i 's)		
m	R/S	m
n	R/S	1
n_1 or H_1	R/S	2
n_2 or H_2	R/S	3
.	.	.
.	.	.
.	.	.
n_{m-1} or H_{m-1}	R/S	m
n_m or H_m	R/S	1 (see Note 1)
X_1	R/S	2
X_2	R/S	3
.	.	.
.	.	.
.	.	.
X_{m-1}	R/S	m
X_m	R/S	0 (see Note 2)

Note 1: If H was entered by mass values h_i , $i = 1, 2, \dots, m$ and $(h_1 + h_2 + \dots + h_m)$ is not between .99 and 1.01 then error code "22" will be displayed after h_m is entered. The user can press "x:t" to display $(h_1 + h_2 + \dots + h_m)$. Ideally, the mass values will always sum to 1 but the user may be using rounded values which do not. If the user wishes to proceed with the K-S test after error code "22" is displayed he should press "A'". This will cause the mass values to be normalized so they will sum to 1. Normally, this should only be done if a more accurate statement of mass values is unavailable.

Note 2: If $(X_1 + X_2 + \dots + X_m) \neq n$ then error code "33" will be displayed. The test cannot proceed.

STEP FOUR - Computing the Test Statistic:

After completing the Initialization and Data Entry sequence the test statistic, t , should be computed.

If $H_0: F(x) = H(x)$ then press A.

If $H_0: F(x) \geq H(x)$ then press B.

If $H_0: F(x) \leq H(x)$ then press C.

After processing the data and computing the appropriate test statistic, t , the calculator will either display t or "44". The latter indicates that the problem is too large for Discrete K-S. The user can recall t from register 00. If t is displayed (always a number between 0 and 1) then the user can proceed with the test.

STEP FIVE - Computing the Significance Level:

After the test statistic is displayed the program has automatically repartitioned the calculator to allow Card 2 to be read into the calculator. The user is cautioned not to press "CP" or "RST" between using Card 1 and Card 2. This is important because certain flags are set in the calculator during the previous steps.

To compute the significance level of the test simply read Card 2, both sides, into the calculator and press "A". If a one-sided test is conducted, then the significance level displayed may be considered exact. If a two-sided test is conducted then the calculator displays an approximate significance level. The following steps may be used to judge the quality of the approximation:

Press	Display
B	upper bound on S.L.
B, x ₂ t	lower bound on S.L.
C	maximum error in point estimate of S.L.
D	recall point estimate of S.L.

After the test is completed the calculator can be restored to normal partitioning by pressing "E".

The user should be aware that the time required to compute a significance level can be considerable. The following table may be used to estimate computing time.

Problem Size:		Time to compute significance level:	
n	m	one-sided test	two-sided test
10	5	3 min, 30 sec	7 min
20	10	45 min	90 min
40	12	2 hours	4 hours

If the user needs the capability to handle larger problems and/or process data quickly a FORTRAN program has been developed by Allen [Ref. 9] for this purpose.

APPENDIX A

CONTINUOUS K-S: ENTRY PROCEDURE, LISTING, AND EXAMPLES

A. ENTRY PROCEDURE

The program is organized in two distinct parts. Card 1 and Card 2. Card 1 should be recorded on a magnetic card using banks 1 and 2 [Ref. 8: pp. VII-2] with the calculator in standard partitioning [Ref. 8: pp. V-22]. Card 2 should also be recorded on banks 1 and 2 but with partitioning 399.69.

It should be noted in the program listing below that Cards 1 and 2 both use the "Dsz" command followed by register numbers greater than 9. The user's manual [Ref. 8: pp. V-63] implies that this will not work but, in fact, it does. The user has to use a special entry technique to get the program steps into the calculator correctly, however. One very convenient way to accomplish this is illustrated easily by an example.

Assume that the steps at one point in the program are "Dsz, 58". The user can first enter "STO, 58", then backstep twice until "42" is in the display (for "STO"). He should then overwrite the "STO" command by pressing "Dsz". This will leave "58" in the display. He should then advance the program pointer one step (with "SST") and continue entering the rest of the program.

B. CONTINUOUS K-S PROGRAM LISTING

CARD 1

000	76	LBL	045	85	+
001	96	WRT	046	43	RCL
002	22	INV	047	68	68
003	86	STF	048	54)
004	03	03	049	42	STD
005	53	(	050	69	69
006	53	(	051	29	CP
007	43	RCL	052	53	(
008	68	68	053	73	RC*
009	23	LNx	054	66	66
010	55	+	055	75	-
011	02	2	056	73	RC*
012	23	LNx	057	65	65
013	54	)	058	54)
014	59	INT	059	77	GE
015	32	X:T	060	00	00
016	02	2	061	71	71
017	45	Yx	062	63	EX*
018	32	X:T	063	66	66
019	54	)	064	63	EX*
020	59	INT	065	65	65
021	42	STD	066	63	EX*
022	67	67	067	66	66
023	29	CP	068	22	INV
024	67	EQ	069	86	STF
025	38	SIN	070	03	03
026	87	IFF	071	01	1
027	03	03	072	44	SUM
028	00	00	073	65	65
029	83	83	074	44	SUM
030	86	STF	075	66	66
031	03	03	076	97	DSZ
032	25	CLR	077	69	69
033	42	STD	078	00	00
034	65	65	079	51	51
035	42	STD	080	61	GTO
036	66	66	081	00	00
037	43	RCL	082	26	26
038	67	67	083	22	INV
039	44	SUM	084	86	STF
040	66	66	085	03	03
041	53	(	086	53	(
042	94	+/-	087	43	RCL
043	85	+	088	67	67
044	01	1			

CONTINUOUS K-S, CARD 1 (con't)

089	55	+	135	98	ADV
090	02	2	136	71	SBR
091	54	)	137	02	02
092	61	GTD	138	60	60
093	00	00	139	98	ADV
094	20	20	140	01	1
095	25	CLR	141	22	INV
096	42	STD	142	90	LST
097	68	68	143	92	RTN
098	92	RTN	144	76	LBL
099	76	LBL	145	38	SIN
100	15	E	146	43	RCL
101	25	CLR	147	59	59
102	07	7	148	42	STD
103	69	DP	149	58	58
104	17	17	150	75	-
105	86	STF	151	01	1
106	08	08	152	54)
107	47	CMS	153	42	STD
108	92	RTN	154	57	57
109	76	LBL	155	73	RC*
110	11	A	156	57	57
111	99	PRT	157	72	ST*
112	72	ST*	158	58	58
113	68	68	159	01	1
114	32	XIT	160	94	+/-
115	01	1	161	44	SUM
116	44	SUM	162	57	57
117	68	68	163	97	DSZ
118	44	SUM	164	58	58
119	59	59	165	01	01
120	43	RCL	166	55	55
121	68	68	167	92	RTN
122	92	RTN	168	76	LBL
123	76	LBL	169	16	A*
124	13	C	170	43	RCL
125	71	SBR	171	59	59
126	02	02	172	42	STD
127	85	85	173	58	58
128	01	1	174	73	RC*
129	22	INV	175	58	58
130	44	SUM	176	23	LNK
131	68	68	177	72	ST*
132	71	SBR	178	58	58
133	96	WRT	179	97	DSZ
134	98	ADV	180	58	58

CONTINUOUS K-S, CARD 1 (con't)

181	01	01
182	74	74
183	18	C'
184	92	RTN
185	76	LBL
186	17	B'
187	43	RCL
188	59	59
189	42	STO
190	58	58
191	73	RC*
192	58	58
193	71	SBR
194	10	E'
195	72	ST*
196	58	58
197	97	DSZ
198	58	58
199	01	01
200	91	91
201	18	C'
202	92	RTN
203	76	LBL
204	18	C'
205	98	ADV
206	98	ADV
207	03	3
208	07	7
209	03	3
210	05	5
211	01	1
212	03	3
213	69	DP
214	01	01
215	03	3
216	01	1
217	03	3
218	06	6
219	02	2
220	01	1
221	03	3
222	02	2
223	03	3
224	05	5
225	69	DP
226	02	02

227	03	3
228	00	0
229	01	1
230	07	7
231	01	1
232	06	6
233	00	0
234	00	0
235	01	1
236	06	6
237	69	DP
238	03	03
239	01	1
240	03	3
241	03	3
242	07	7
243	01	1
244	03	3
245	00	0
246	00	0
247	00	0
248	00	0
249	69	DP
250	04	04
251	69	DP
252	05	05
253	69	DP
254	00	00
255	98	ADV
256	01	1
257	22	INV
258	90	LST
259	92	RTN
260	02	2
261	04	4
262	03	3
263	01	1
264	03	3
265	03	3
266	04	4
267	01	1
268	03	3
269	07	7
270	69	DP
271	02	02
272	01	1

CONTINUOUS K-S, CARD 1 (con't)

273	06	6
274	01	1
275	03	3
276	03	3
277	07	7
278	01	1
279	03	3
280	69	DP
281	03	03
282	69	DP
283	05	05
284	92	RTN
285	43	RCL
286	59	59
287	75	-
288	01	1
289	54)
290	42	STD
291	58	58
292	73	RC*
293	58	58
294	32	XIT
295	01	1
296	22	INV
297	44	SUM
298	58	58
299	73	RC*
300	58	58

301	32	XIT
302	77	GE
303	03	03
304	06	06
305	92	RTN
306	01	1
307	44	SUM
308	58	58
309	97	DSZ
310	58	58
311	02	02
312	92	92
313	71	SBR
314	38	SIN
315	98	ADV
316	98	ADV
317	71	SBR
318	02	02
319	60	60
320	98	ADV
321	01	1
322	22	INV
323	90	LST
324	91	R/S

CONTINUOUS K-S, CARD 2

000 76 LBL
 001 19 D'
 002 77 GE
 003 00 00
 004 06 06
 005 32 XIT
 006 92 RTN
 007 76 LBL
 008 12 B
 009 86 STF
 010 04 04
 011 61 GTD
 012 11 A
 013 76 LBL
 014 13 C
 015 86 STF
 016 05 05
 017 76 LBL
 018 11 A
 019 25 CLR
 020 91 R/S
 021 76 LBL
 022 16 A'
 023 42 STD
 024 63 63
 025 91 R/S
 026 42 STD
 027 62 62
 028 61 GTD
 029 00 00
 030 55 55
 031 76 LBL
 032 17 B'
 033 86 STF
 034 01 01
 035 42 STD
 036 63 63
 037 01 1
 038 42 STD
 039 62 62
 040 91 R/S
 041 42 STD
 042 62 62
 043 61 GTD
 044 00 00

045 55 55
 046 76 LBL
 047 18 C'
 048 86 STF
 049 02 02
 050 42 STD
 051 63 63
 052 91 R/S
 053 42 STD
 054 62 62
 055 00 0
 056 42 STD
 057 68 68
 058 42 STD
 059 67 67
 060 42 STD
 061 65 65
 062 43 RCL
 063 59 59
 064 42 STD
 065 66 66
 066 85 +
 067 01 1
 068 42 STD
 069 64 64
 070 54)
 071 42 STD
 072 00 00
 073 89 n
 074 94 +/-
 075 72 ST*
 076 00 00
 077 73 RC*
 078 64 64
 079 32 XIT
 080 01 1
 081 44 SUM
 082 64 64
 083 73 RC*
 084 64 64
 085 67 EQ
 086 01 01
 087 46 46
 088 01 1

CONTINUOUS K-S, CARD 2 (con't)

089	22	INV	135	42	STD
090	44	SUM	136	67	67
091	64	64	137	00	0
092	32	XIT	138	42	STD
093	71	SBR	139	65	65
094	01	01	140	01	1
095	83	83	141	44	SUM
096	42	STD	142	64	64
097	00	00	143	61	GTD
098	43	RCL	144	01	01
099	44	64	145	49	49
100	55	÷	146	01	1
101	43	RCL	147	44	SUM
102	59	59	148	65	65
103	54	)	149	97	DSZ
104	75	-	150	66	66
105	43	RCL	151	00	00
106	00	00	152	77	77
107	54	)	153	87	IFF
108	32	XIT	154	04	04
109	43	RCL	155	01	01
110	68	68	156	73	73
111	19	D'	157	87	IFF
112	42	STD	158	05	05
113	68	68	159	01	01
114	43	RCL	160	78	78
115	64	64	161	43	RCL
116	75	-	162	67	67
117	01	1	163	32	XIT
118	75	-	164	43	RCL
119	43	RCL	165	68	68
120	65	65	166	19	D'
121	54	)	167	10	E'
122	55	÷	168	65	x
123	43	RCL	169	02	2
124	59	59	170	54)
125	54	)	171	99	PRT
126	94	+/-	172	91	R/S
127	85	+	173	43	RCL
128	43	RCL	174	68	68
129	00	00	175	10	E'
130	54	)	176	99	PRT
131	32	XIT	177	91	R/S
132	43	RCL	178	43	RCL
133	67	67	179	67	67
134	19	D'	180	10	E'

CONTINUOUS K-S, CARD 2 (con't)

181	99	PRT	227	22	INV
182	91	R/S	228	77	GE
183	87	IFF	229	02	02
184	01	01	230	50	50
185	02	02	231	32	XIT
186	03	03	232	75	-
187	87	IFF	233	43	RCL
188	02	02	234	63	63
189	02	02	235	54)
190	19	19	236	32	XIT
191	75	-	237	43	RCL
192	43	RCL	238	62	62
193	63	63	239	75	-
194	54	)	240	43	RCL
195	55	÷	241	63	63
196	43	RCL	242	54)
197	62	62	243	35	1/X
198	54	)	244	65	x
199	36	PGM	245	32	XIT
200	19	19	246	54)
201	12	B	247	92	RTN
202	92	RTN	248	00	0
203	65	x	249	92	RTN
204	43	RCL	250	01	1
205	63	63	251	92	RTN
206	54	)	252	76	LBL
207	45	YX	253	10	E'
208	43	RCL	254	42	STD
209	62	62	255	00	00
210	54	)	256	01	1
211	94	+/-	257	75	-
212	22	INV	258	43	RCL
213	23	LNK	259	00	00
214	94	+/-	260	54)
215	85	+	261	42	STD
216	01	1	262	66	66
217	54	)	263	65	x
218	92	RTN	264	43	RCL
219	32	XIT	265	59	59
220	43	RCL	266	54)
221	63	63	267	59	INT
222	77	GE	268	85	+
223	02	02	269	01	1
224	48	48	270	54)
225	43	RCL	271	42	STD
226	62	62	272	68	68

CONTINUOUS K-S, CARD 2 (con't)

273	43	RCL	319	44	SUM
274	59	59	320	65	65
275	42	STD	321	44	SUM
276	67	67	322	56	56
277	35	1/X	323	22	INV
278	42	STD	324	44	SUM
279	58	58	325	67	67
280	43	RCL	326	43	RCL
281	00	00	327	58	58
282	42	STD	328	22	INV
283	57	57	329	44	SUM
284	00	0	330	66	66
285	42	STD	331	44	SUM
286	65	65	332	57	57
287	42	STD	333	97	DSZ
288	61	61	334	68	68
289	01	1	335	02	02
290	94	+/-	336	93	93
291	42	STD	337	43	RCL
292	56	56	338	61	61
293	71	SBR	339	65	X
294	03	03	340	43	RCL
295	46	46	341	00	00
296	42	STD	342	54)
297	60	60	343	98	ADV
298	43	RCL	344	98	ADV
299	66	66	345	92	RTN
300	45	YX	346	43	RCL
301	43	RCL	347	65	65
302	67	67	348	42	STD
303	54	)	349	63	63
304	49	PRD	350	32	XIT
305	60	60	351	00	0
306	43	RCL	352	22	INV
307	57	57	353	67	EQ
308	45	YX	354	03	03
309	43	RCL	355	58	58
310	56	56	356	01	1
311	54	)	357	92	RTN
312	49	PRD	358	01	1
313	60	60	359	42	STD
314	43	RCL			
315	60	60			
316	44	SUM			
317	61	61			
318	01	1			

CONTINUOUS K-S, CARD 2 (con't)

360	62	62
361	43	RCL
362	63	63
363	94	+/-
364	85	+
365	43	RCL
366	59	59
367	42	STD
368	64	64
369	54)
370	32	XIT
371	43	RCL
372	63	63
373	22	INV
374	77	GE
375	03	03
376	80	80
377	32	XIT
378	42	STD
379	63	63
380	43	RCL
381	64	64
382	55	÷
383	43	RCL
384	63	63
385	54)
386	49	PRD
387	62	62
388	01	1
389	22	INV
390	44	SUM
391	64	64
392	97	DSZ
393	63	63
394	03	03
395	80	80
396	43	RCL
397	62	62
398	92	RIN

C. CONTINUOUS K-S EXAMPLE PROBLEMS

1. Example 1

a. Problem:

H_0 : $F(x) = H(x)$ for all x , where $H = \text{Uniform}(0,5)$, i.e.,

$$H(x) = \begin{cases} 1 & , & x > 5 \\ x/5 & , & 0 \leq x \leq 5 \\ 0 & , & x < 0 \end{cases}$$

H_1 : $F(x) \neq H(x)$ for some x

Sample size = $n = 10$

Sample data: 0.8, 4.0, 0.2, 2.6, 3.8, 0.6, 1.0, 4.8, 1.2, 1.4

b. Solution:

Read both sides of Card 1 into the calculator, then:

ENTER	PRESS	DISPLAY	PRINTOUT	COMMENTS
	E	399.69		new partitioning
0.8	A	1	0.8	sample data
4.0	A	2	4.0	
.	.	.	.	
.	.	.	.	
.	.	.	.	
1.4	A	10	1.4	sorted sample data
	C	1	INPUT DATA	
			0.2 01	
			0.6 02	
			.	
			.	ignore
			.	
			4.8 10	
			0. 11	
			0. 12	
			.	
			.	

(con't)

After completing the previous steps using Card 1 read both sides of Card 2 into the calculator. Do not press "CP" or "RST". Complete the test as follows:

ENTER	PRESS	DISPLAY	PRINTOUT	COMMENTS
	A	0		two-tailed test
0	C	0		H = Uniform (0,5)
5	R/S	.2073748895	.2073748895	significance level [Time: 1 min. 33 sec]

Since the test conducted was a two-tailed test the significance level computed is approximate. The user is assured that the true significance level is no greater than the value computed. The user may recall the test statistic $t = .32$ from register 00.

2. Example 2

a. Problem:

$H_0 : F(x) \leq H(x)$ for all x , where $H = \text{Normal}(3, 2^2)$

$H_1 : F(x) > H(x)$ for some x

Sample size = $n = 5$

Sample data: 1.462, -0.311, 0.555, 5.711, -0.078

b. Solution:

Read both sides of card 1 into the calculator, then:

ENTER	PRESS	DISPLAY	PRINTOUT	COMMENTS
	E	399.69		new partitioning
1.462	A	1	1.462	sample data
-0.311	A	2	-0.311	
0.555	A	3	0.555	
5.711	A	4	5.711	
-0.078	A	5	-0.078	
	C	1	INPUT DATA	[Time: 30 sec]
			-0.311 01	Sorted Sample Data
			-0.078 02	
			0.555 03	
			1.462 04	
			5.711 05	
			0. 06	ignore
			0. 07	
			.	

Read Card 2, both sides, into the calculator, then:

ENTER	PRESS	DISPLAY	PRINTOUT	COMMENTS
	B	0		one-tailed test
3	A	3		$H = \text{Normal}(3, 2^2)$
2	R/S	.0201689866	.0201689866	significance level
				[Time: 53 sec]

The user may recall the test statistic $t = .5792534154$ from register 00.

3. Example 3

a. Problem:

$H_0: F(x) = H(x)$ for all x , where

$$H(x) = \begin{cases} 0 & , \quad x < 0 \\ x^2/4 & , \quad 0 \leq x \leq 2 \\ 1 & , \quad x > 2 \end{cases}$$

$H_1: F(x) \neq H(x)$ for some x

Sample size $n = 10$

Sample data: 1.8, 1.0, 1.3, 0.5, 1.98, 0.95, 1.91,

0.75, 1.85, 1.6

b. Discussion:

Continuous K-S does not have a subroutine to evaluate the hypothesized CDF H for this problem. This is an ideal situation to invoke the probability integral transformation. Under the null hypothesis X has CDF H , thus, $H(X)$ is distributed uniform $(0,1)$ under the null hypothesis. If we transform each sample data value with H , defined above, then we can proceed with the K-S test using a uniform $(0,1)$ distribution in place of the original hypothesized distribution.

c. Solution:

Read both sides of Card 1 into the calculator, then:

ENTER	PRESS	DISPLAY	PRINTOUT	COMMENT
	E	399.69		new partitioning
1.8	A	1	1.8	sample data
1.0	A	2	1.0	
.	.	.	.	
.	.	.	.	
1.6	A	10	1.6	[Time: 1 min, 20 sec]
	C	1	INPUT DATA	
			0.5 01	
			0.75 02	
			.	sorted sample data
			.	
			1.98 10	
			0. 11	
			0. 12	ignore
			.	
			.	
			.	
	GTO 325	1		Transformation Subroutine H
	LRN	325 00		
	LBL	326 00		
	E'	327 00		
	X ²	328 00		
	÷	329 00		
	4	330 00		
	)	331 00	
	INV SBR	332 00		
	LRN	1		Subroutine test
	E'	1		
2	B'	TRANSFORMED DATA		Transformed data
		0.0625 01		
		0.140625 02		
		0.225625 03		
		0.25 04		
		0.4225 05		
		0.64 06		
		0.81 07		
		0.855625 08		
		0.912025 09		
		0.9801 10		
		0. 11		ignore
		0. 12		
		.		
		.		

Read both sides of Card 2 into the calculator, then:

ENTER	PRESS	DISPLAY	PRINTOUT	COMMENT
	A	0		two-sided test
0	C'	0		uniform (0,1)
1	R/S	.7275048241	.7275048421	upper bound on significance level [Time: 2 min]

If the significance level computed had been .1 or less we could consider it exact. With as value as large as that computed, however, we should consider it an upper bound on the true significance level and conclude that the sample data and the null hypothesis are in close agreement. The user may recall the test statistic $t = .21$ from register 00.

4. Example 4

a. Problem:

$H_0 : F(x) \geq H(x)$ for all x , where $H = \text{lognormal}(3, 5^2)$

$H_1 : F(x) < H(x)$ for some x

Sample size = $n = 7$

Sample data: 99.31, 22.47, .0608, 3294.5, 4.95, 14.88, 29.96

b. Discussion:

This problem demonstrates the use of the natural log transformation. It is appropriate when the hypothesized distribution is lognormal. Recall that X is distributed lognormal (μ, σ^2) if and only if $\ln(X)$ is distributed normal (μ, σ^2) . We rely on the natural log transformation subroutine incorporated into Card 1 of Continuous K-S to transform our sample data. We then test the transformed data against a normal $(3, 5^2)$ CDF using Card 2.

c. Solution:

Read both sides of Card 1 into the calculator, then:

ENTER	PRESS	DISPLAY	PRINTOUT	COMMENT
	E	399.69		new partitioning
99.31	A	1	99.31	} sample data
22.47	A	2	22.47	
0.0608	A	3	0.0608	
3294.5	A	4	3294.5	
4.95	A	5	4.95	
14.88	A	6	14.88	
29.96	A	7	29.96	

ENTER	PRESS	DISPLAY	PRINTOUT	COMMENT
C		1	INPUT DATA	[Time: 46 sec]
			0.0608 01	
			4.95 02	
			14.88 03	
			22.47 04	sorted sample data
			29.96 05	
			99.31 06	
			3294.5 07	
			0. 08	
			0. 09	ignore
			.	
			.	
A'		1	TRANSFORMED DATA	
			-2.80016549 01	
			1.599387577 02	
			2.700018029 03	Transformed data
			3.112181086 04	
			3.399863159 05	
			4.598246271 06	
			8.10000969 07	
			0. 08	ignore
			0. 09	
			.	
			.	

Read both sides of Card 2 into the calculator, then:

ENTER	PRESS	DISPLAY	PRINTOUT	COMMENT
	C	0		One-sided test
3	A'	3		normal (3, 5 ²)
5	R/S	.3672246357	.3672246357	significance level
				[Time 1 min, 25 sec]

The user may recall test statistic $t = .2468346856$ from register 00.

APPENDIX B

DISCRETE K-S: ENTRY PROCEDURE, LISTING, AND EXAMPLES

A. ENTRY PROCEDURE

The program is organized in two distinct parts, Card 1 and Card 2. Card 1 should be recorded on a magnetic card using banks 1 and 2 [Ref. 8: pp. VII-2] with the calculator in standard partitioning [Ref. 8: pp. V-22]. Card 2 should also be recorded in banks 1 and 2 but with partitioning 399.69.

It should be noted in the program listing below that Cards 1 and 2 both use the "Dsz" command followed by register numbers greater than 9. The user's manual [Ref. 8: pp. V-63] implies that this will not work but, in fact, it does. The user has to use a special entry technique to get the program steps into the calculator correctly, however. One very convenient way to accomplish this is illustrated easily by an example.

Assume the steps at one point in the program are "Dsz, 58". The user can first enter "STO, 58", then backstep twice until "42" is in the display (for "STO"). He should then overwrite the "STO" command by pressing "Dsz". This will leave "58" in the display. He should advance the program pointer one step (with "SST") and continue entering the rest of the program.

Discrete K-S uses the "HIR" command, explained in detail in Appendix D. It is represented by machine code "82" and thus must be entered with a special procedure. A convenient way to enter "HIR" is to precede it with "STO", enter "82", and backstep twice, leaving "42" (for "STO") in the display. Delete the "STO" command with "del", advance the program pointer one step, and continue entering the program. When "HIR" is followed by another two-digit merged code, e.g., "HIR, 16", the entry procedure should be used twice, the first time to enter "82" and the second time to enter "16".

B. DISCRETE K-S PROGRAM LISTING

CARD 1

000	76	LBL	045	20	20
001	15	E	046	43	RCL
002	25	CLR	047	00	00
003	47	CMS	048	22	INV
004	86	STF	049	77	GE
005	00	00	050	00	00
006	61	GTO	051	34	34
007	00	00	052	22	INV
008	16	16	053	87	IFF
009	76	LBL	054	00	00
010	10	E	055	16	R'
011	22	INV	056	01	1
012	86	STF	057	93	.
013	00	00	058	00	0
014	25	CLR	059	01	1
015	47	CMS	060	32	XIT
016	22	INV	061	43	RCL
017	86	STF	062	45	45
018	04	04	063	77	GE
019	91	R/S	064	03	03
020	42	STD	065	87	87
021	41	41	066	32	XIT
022	85	+	067	93	.
023	01	1	068	09	9
024	54	)	069	09	9
025	32	XIT	070	77	GE
026	43	RCL	071	03	03
027	41	41	072	97	87
028	91	R/S	073	76	LBL
029	42	STD	074	16	R'
030	42	42	075	43	RCL
031	01	1	076	41	41
032	42	STD	077	85	+
033	00	00	078	01	1
034	91	R/S	079	54)
035	72	ST*	080	32	XIT
036	00	00	081	02	2
037	22	INV	082	01	1
038	87	IFF	083	42	STD
039	00	00	084	00	00
040	00	00	085	01	1
041	44	44	086	42	STD
042	44	SUM	087	44	44
043	45	45	088	91	R/S
044	69	OP			

DISCRETE K-S, CARD 1 (con't)

089	72	ST*	135	42	42
090	00	00	136	76	LBL
091	44	SUM	137	13	C
092	43	43	138	86	STF
093	69	DP	139	01	01
094	20	20	140	86	STF
095	01	1	141	02	02
096	44	SUM	142	87	IFF
097	44	44	143	04	04
098	43	RCL	144	03	03
099	44	44	145	01	01
100	22	INV	146	86	STF
101	77	GE	147	04	04
102	00	00	148	22	INV
103	88	88	149	87	IFF
104	43	RCL	150	00	00
105	42	42	151	01	01
106	32	XIT	152	70	70
107	43	RCL	153	43	RCL
108	43	43	154	45	45
109	22	INV	155	35	1/X
110	67	EQ	156	42	STD
111	03	03	157	45	45
112	91	91	158	43	RCL
113	25	CLR	159	41	41
114	91	R/S	160	42	STD
115	76	LBL	161	44	44
116	11	A	162	43	RCL
117	86	STF	163	45	45
118	01	01	164	64	PD*
119	22	INV	165	44	44
120	86	STF	166	97	DSZ
121	02	02	167	44	44
122	61	GTD	168	01	01
123	01	01	169	64	64
124	42	42	170	43	RCL
125	76	LBL	171	42	42
126	12	B	172	35	1/X
127	22	INV	173	42	STD
128	86	STF	174	43	43
129	02	02	175	02	2
130	22	INV	176	01	1
131	86	STF	177	42	STD
132	01	01	178	00	00
133	61	GTD	179	43	RCL
134	01	01	180	41	41

DISCRETE K-S, CARD 1 (con't)

181	42	STD	227	43	43
182	44	44	228	97	DSZ
183	43	RCL	229	44	44
184	43	43	230	02	02
185	64	PD*	231	08	08
186	00	00	232	01	1
187	01	1	233	42	STD
188	44	SUM	234	00	00
189	00	00	235	42	STD
190	97	DSZ	236	50	50
191	44	44	237	42	STD
192	01	01	238	51	51
193	83	83	239	02	2
194	43	RCL	240	01	1
195	41	41	241	42	STD
196	75	-	242	43	43
197	01	1	243	43	RCL
198	54	)	244	41	41
199	42	STD	245	42	STD
200	44	44	246	44	44
201	02	2	247	00	0
202	01	1	248	42	STD
203	42	STD	249	47	47
204	00	00	250	42	STD
205	01	1	251	48	48
206	42	STD	252	73	RC*
207	43	43	253	00	00
208	73	RC*	254	75	-
209	00	00	255	73	RC*
210	69	DP	256	43	43
211	20	20	257	54)
212	74	SM*	258	42	STD
213	00	00	259	45	45
214	22	INV	260	94	+/-
215	87	IFF	261	32	XIT
216	00	00	262	43	RCL
217	02	02	263	48	48
218	28	28	264	77	GE
219	73	RC*	265	02	02
220	43	43	266	77	77
221	32	XIT	267	32	XIT
222	01	1	268	42	STD
223	44	SUM	269	48	48
224	43	43	270	43	RCL
225	32	XIT	271	00	00
226	74	SM*	272	42	STD

DISCRETE K-S, CARD 1 (con't)

273	50	50
274	61	GTD
275	02	02
276	92	92
277	43	RCL
278	45	45
279	32	XIT
280	43	RCL
281	47	47
282	77	GE
283	02	02
284	92	92
285	32	XIT
286	42	STD
287	47	47
288	43	RCL
289	00	00
290	42	STD
291	51	51
292	01	1
293	44	SUM
294	00	00
295	44	SUM
296	43	43
297	97	DSZ
298	44	44
299	02	02
300	52	52
301	87	IFF
302	01	01
303	03	03
304	12	12
305	43	RCL
306	47	47
307	82	HIR
308	04	04
309	61	GTD
310	03	03
311	31	31
312	87	IFF
313	02	02
314	03	03
315	27	27
316	43	RCL
317	47	47
318	32	XIT

319	43	RCL
320	48	48
321	77	GE
322	03	03
323	27	27
324	61	GTD
325	03	03
326	05	05
327	43	RCL
328	48	48
329	82	HIR
330	04	04
331	07	7
332	69	DP
333	17	17
334	01	1
335	75	-
336	82	HIR
337	14	14
338	95	=
339	65	x
340	43	RCL
341	42	42
342	95	=
343	85	+
344	02	2
345	95	=
346	59	INT
347	42	STD
348	59	59
349	43	RCL
350	42	42
351	82	HIR
352	02	02
353	43	RCL
354	41	41
355	82	HIR
356	03	03
357	05	5
358	05	5
359	75	-

DISCRETE K-S, CARD 1 (con't)

360	82	HIR
361	13	13
362	95	=
363	32	XIT
364	43	RCL
365	59	59
366	77	GE
367	03	03
368	84	84
369	93	.
370	00	0
371	00	0
372	00	0
373	00	0
374	00	0
375	00	0
376	00	0
377	00	0
378	01	1
379	42	STD
380	56	56
381	82	HIR
382	14	14
383	91	R/S
384	04	4
385	04	4
386	91	R/S
387	32	XIT
388	02	2
389	02	2
390	91	R/S
391	32	XIT
392	03	3
393	03	3
394	91	R/S

DISCRETE K-S, CARD 2

000	76	LBL	045	82	HIR
001	12	B	046	06	06
002	82	HIR	047	22	INV
003	13	13	048	86	STF
004	75	-	049	01	01
005	82	HIR	050	71	SBR
006	12	12	051	88	DMS
007	95	=	052	82	HIR
008	32	XIT	053	05	05
009	82	HIR	054	85	+
010	13	13	055	82	HIR
011	85	+	056	16	16
012	82	HIR	057	95	=
013	12	12	058	42	STD
014	95	=	059	00	00
015	91	R/S	060	82	HIR
016	76	LBL	061	15	15
017	13	C	062	65	x
018	82	HIR	063	82	HIR
019	12	12	064	16	16
020	91	R/S	065	55	+
021	76	LBL	066	02	2
022	14	D	067	95	=
023	82	HIR	068	82	HIR
024	13	13	069	02	02
025	91	R/S	070	32	XIT
026	76	LBL	071	82	HIR
027	11	R	072	12	12
028	22	INV	073	94	+/-
029	87	IFF	074	85	+
030	01	01	075	43	RCL
031	00	00	076	00	00
032	81	81	077	95	=
033	22	INV	078	82	HIR
034	97	IFF	079	03	03
035	02	02	080	91	R/S
036	00	00	081	71	SBR
037	43	43	082	88	DMS
038	71	SBR	083	82	HIR
039	88	DMS	084	05	05
040	82	HIR	085	91	R/S
041	06	06	086	76	LBL
042	91	R/S	087	88	DMS
043	71	SBR	088	82	HIR
044	88	DMS			

DISCRETE X-S, CARD 2 (con't)

089	13	13	
090	85	+	
091	01	1	
092	95	=	
093	42	STD	
094	62	62	
095	42	STD	
096	58	58	
097	01	1	
098	72	ST*	
099	62	62	
100	02	2	
101	42	STD	
102	00	00	
103	01	1	
104	82	HIR	
105	07	07	
106	00	0	
107	42	STD	
108	60	60	
109	01	1	
110	42	STD	
111	69	69	
112	42	STD	
113	64	64	
114	43	RCL	
115	59	59	
116	42	STD	
117	68	68	
118	43	RCL	
119	69	69	
120	71	SBR	
121	03	03	
122	05	05	
123	32	X:T	
124	00	0	
125	67	E9	
126	01	01	
127	55	55	
128	32	X:T	
129	45	YX	
130	43	RCL	
131	64	64	
132	95	=	
133	42	STD	
134	57	57	
135	43	RCL	
136	69	69	
137	75	-	
138	01	1	
139	95	=	
140	82	HIR	
141	08	08	
142	71	SBR	
143	02	02	
144	68	68	
145	49	PRD	
146	57	57	
147	73	RC*	
148	62	62	
149	49	PRD	
150	57	57	
151	43	RCL	
152	57	57	
153	44	SUM	
154	60	60	
155	01	1	
156	44	SUM	
157	69	69	
158	44	SUM	
159	62	62	
160	94	+/-	
161	44	SUM	
162	64	64	
163	43	RCL	
164	00	00	
165	32	X:T	
166	43	RCL	
167	69	69	
168	22	INV	
169	77	GE	
170	01	01	
171	18	18	
172	01	1	
173	75	-	
174	43	RCL	
175	60	60	
176	95	=	
177	72	ST*	
178	62	62	
179	01	1	
180	42	STD	

DISCRETE K-S, CARD 2 (con't)

181 69 69
 182 44 SUM
 183 00 00
 184 82 HIR
 185 37 37
 186 82 HIR
 187 17 17
 188 42 STD
 189 64 64
 190 43 RCL
 191 68 68
 192 32 XIT
 193 43 RCL
 194 00 00
 195 77 GE
 196 02 02
 197 08 08
 198 00 0
 199 42 STD
 200 60 60
 201 43 RCL
 202 58 58
 203 42 STD
 204 62 62
 205 61 STD
 206 01 01
 207 18 18
 208 01 1
 209 94 +/-
 210 44 SUM
 211 68 68
 212 43 RCL
 213 58 58
 214 42 STD
 215 62 62
 216 00 0
 217 82 HIR
 218 08 08
 219 42 STD
 220 61 61
 221 82 HIR
 222 12 12
 223 82 HIR
 224 07 07
 225 42 STD
 226 67 67

227 71 SBR
 228 02 02
 229 68 68
 230 42 STD
 231 60 60
 232 73 RC*
 233 62 62
 234 49 PRD
 235 60 60
 236 43 RCL
 237 69 69
 238 71 SBR
 239 03 03
 240 05 05
 241 45 YX
 242 43 RCL
 243 67 67
 244 95 =
 245 49 PRD
 246 60 60
 247 43 RCL
 248 60 60
 249 44 SUM
 250 61 61
 251 01 1
 252 44 SUM
 253 62 62
 254 44 SUM
 255 69 69
 256 82 HIR
 257 38 38
 258 94 +/-
 259 44 SUM
 260 67 67
 261 97 DSZ
 262 68 68
 263 02 02
 264 27 27
 265 43 RCL
 266 61 61
 267 92 RTN
 268 00 0
 269 32 XIT
 270 82 HIR
 271 18 18
 272 67 EQ

DISCRETE K-S, CARD 2 (con't)

273 03
 274 03
 275 42 STD
 276 66 66
 277 82 HIR
 278 17 17
 279 42 STD
 280 65 65
 281 01 1
 282 42 STD
 283 63 63
 284 43 RCL
 285 65 65
 286 55 +
 287 43 RCL
 288 66 66
 289 95 =
 290 49 PRD
 291 63 63
 292 01 1
 293 94 +/-
 294 44 SUM
 295 65 65
 296 97 DSZ
 297 66 66
 298 02 02
 299 84 84
 300 43 RCL
 301 63 63
 302 92 RTN
 303 01 1
 304 92 RTN
 305 22 INV
 306 87 IFF
 307 01 01
 308 03 03
 309 64 64
 310 94 +/-
 311 95 +
 312 82 HIR
 313 12 12
 314 85 +
 315 01 1
 316 95 =
 317 55 +
 318 82 HIR

319 12 12
 320 95 =
 321 75 -
 322 82 HIR
 323 14 14
 324 95 =
 325 85 +
 326 43 RCL
 327 56 56
 328 95 =
 329 32 XIT
 330 43 RCL
 331 01 01
 332 77 GE
 333 03 03
 334 91 91
 335 82 HIR
 336 13 13
 337 42 STD
 338 63 63
 339 73 RC*
 340 63 63
 341 22 INV
 342 77 GE
 343 03 03
 344 49 49
 345 97 DSZ
 346 63 63
 347 03 03
 348 39 39
 349 22 INV
 350 87 IFF
 351 01 01
 352 03 03
 353 55 55
 354 92 RTN
 355 01 1
 356 44 SUM
 357 63 63
 358 01 1
 359 75 -

DISCRETE K-S, CARD 2 (con't)

360	73	RC*
361	63	63
362	95	=
363	92	RTN
364	75	-
365	01	1
366	95	=
367	55	÷
368	82	HIR
369	12	12
370	95	=
371	85	+
372	82	HIR
373	14	14
374	75	-
375	43	RCL
376	56	56
377	95	=
378	32	X/T
379	82	HIR
380	13	13
381	75	-
382	01	1
383	95	=
384	42	STD
385	63	63
386	73	RC*
387	63	63
388	77	GE
389	03	03
390	35	35
391	00	0
392	92	RTN
393	76	LBL
394	15	E
395	06	6
396	69	DP
397	17	17
398	91	R/S

C. DISCRETE K-S EXAMPLE PROBLEMS

1. Example 1

a. Problem:

H_0 : $F(x) = H(x)$ for all x , where H is defined below

H_1 : $F(x) \neq H(x)$ for some x

Number of cells = $m = 5$

Sample size = $n = 10$

	CELL NUMBER (i)				
	1	2	3	4	5
mass value (h_i):	.2	.2	.2	.2	.2
cumulative mass value (H_i):	.2	.4	.6	.8	1.0
Number of observations (X_i):	3	3	4	0	0

b. Solution:

Read both sides of Card 1 into the calculator, then:

COMMENT	ENTER	PRESS	DISPLAY	COMMENT
initialize		E	0	H defined with h_i 's
no. of cells	5	R/S	5	
sample size	10	R/S	1	
cell mass values	.2	R/S	2	cell number of next mass value entry
	.2	R/S	3	
	.2	R/S	4	
	.2	R/S	5	
	.2	R/S	1	
observations per cell (frequency count)	3	R/S	2	cell number of next frequency count
	3	R/S	3	
	4	R/S	4	
	0	R/S	5	
	0	R/S	0	
		A	.4	test statistic of two-sided test [Time: 22 sec]

Read both sides of Card 2 into the calculator, then:

PRESS	DISPLAY	COMMENT
A	.0414007042	point estimate of significance level [Time: 7 min]
B	.0416172032	upper bound on significance level
x't	.0411842053	lower bound on significance level
C	.000216499	maximum error in point estimate
D	.0414007042	recall point estimate
E	479.59	return TI-59 to normal partitioning

The user can perform the same K-S test by initializing Card 1 with "E'" and then entering H_i values instead of h_i values. The test results will be the same.

2. Example 2

a. Problem:

$H_0 : F(x) \geq H(x)$ for all x , where H is defined below

$H_1 : F(x) < H(x)$ for some x

Number of cells = $m = 3$

Sample size = $n = 15$

	CELL NUMBER (i)		
	1	2	3
mass value (h_i):	.3624	.4167	.2209
cumulative mass value (H_i)	.3624	.7791	1.0
number of observations (\bar{X}_i)	5	3	7

b. Solution:

Read both sides of Card 1 into the calculator, then:

COMMENT	ENTER	PRESS	DISPLAY	COMMENT
initialize		E'	0	H defined with H_i 's
no. of cells	3	R/S	3	
sample size	15	R/S	1	cell number of next
cumulative	.3624	R/S	2	cumulative mass
cell mass	.7791	R/S	3	value
values	1.0	R/S	1	
observations	5	R/S	2	cell number of next
per cell	3	R/S	3	frequency count
(frequency counts)	7	R/S	0	

B .245766667 test statistic of
one-sided test
[Time: 15 sec]

Read both sides of Card 2 into the calculator, then:

PRESS	DISPLAY	COMMENT
A	.0395671995	significance level [Time: 11 min]
E	479.59	return TI-59 to normal partitioning

APPENDIX C

CONDENSED USER INSTRUCTIONS

The following two pages are condensed user instructions for Continuous K-S and Discrete K-S, respectively. It is recommended that the reader familiarize himself with the more expanded discussion of programs in sections IV and V above before relying on the condensed instructions.

The condensed instructions for both programs are written for a complete K-S test. It is possible to use Continuous K-S to evaluate a known test statistic from a continuous K-S test. The procedure is as follows.

STEP	PROCEDURE	ENTER	PRESS	DISPLAY
1.	Repartition T1-59	7	Op 17	399.69
2.	Enter both sides of Card 2 (Continuous K-S)			
3.	enter sample size	n	STO 59	n
4.	enter test statistic	t	STO 00	t
5.	compute significance level		E'	S.L.

If the test was one-sided the significance level computed is exact. If the test was two-sided the result should be doubled. The doubled value is an upper bound on the exact significance level.

CONTINUOUS K-S

Card 1 (banks 1 & 2): standard partitioning
Card 2 (banks 1 & 2): 399.69 partitioning

Applied Statistics Module
Printer optional

Purpose: K-S test on continuous random variable with unknown CDF, F. Maximum sample size $n = 54$. Direction of test specified by null hypothesis (H_0). Alternative hypothesis (H_1) is negation of H_0 . Hypothesized CDF, H, can be uniform, normal, Weibull, or exponential. If another H is desired the user can add a subroutine transforming the desired H to one of the above distributions. Program computes exact significance level (S.L.) for a one-sided test and an upper bound on S.L. for two-sided test.

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS	DISPLAY	PRINTOUT
1	Enter both sides of Card 1				
2	Initialize		B	399.69	
3	Enter sample data	X_1 ($i=1, 2, \dots, n$)	A	1	X_i
4	Sort data		C	1	$X_{(1)}, \dots, X_{(n)}$
5	Transforming data (optional step; normally omitted): If hypothesized CDF, H, is NOT uniform, normal, Weibull, or exponential then the user may enter a subroutine to transform H to one of those distributions. The subroutine must begin with "LBL R" and end with "INV SBR". For a transformation M the subroutine should be written to transform some value c to M(c) with c in the x-register when the subroutine is called and M(c) is returned to the main program. Use only registers n+1 through 57 (sample size = n) and limit subroutine to 75 steps. After subroutine entered and validated, press "B". M($X_{(n)}$) will be displayed. If user wishes to transform each sample value x to $\ln(x)$ press "A". The transformation subroutine is already provided and is useful to transform lognormal (μ, σ^2) data to normal (μ, σ^2). Do not press "B". Proceed with test with the new distribution substituted for original H.				
STEP	PROCEDURE	ENTER	PRESS	DISPLAY	PRINTOUT
6	Enter both sides of Card 2				
7	Choose direction of test:				
	If $H_0: F(x) = H(x)$		A	0	
	If $H_0: F(x) \geq H(x)$		B	0	
	If $H_0: F(x) \leq H(x)$		C	0	
8	Specify H for test:				
	If H = normal (μ, σ^2)	μ σ	A' R/S	μ S.L.	S.L.
	If H = exponential (λ)	λ 1	B' R/S	1 S.L.	S.L.
	If H = Weibull (λ, α)	λ α	B' R/S	1 S.L.	S.L.
	If H = uniform (a, b)	a b	C' R/S	a S.L.	S.L.
9	The test statistic can be recalled from register 20.				

DISCRETE K-S

Card 1 (banks 1 & 2): standard partitioning
Card 2 (banks 1 & 2): 399.69 partitioning

Any Library Module
Does not use printer

Purpose: K-S test on discrete random variable with unknown CDF. F. For sample size n and random variable with m possible outcomes (cells) the program will handle any problem with $n+m \leq 54$. Maximum number of cells: 20. If $n+m$ slightly exceeds 54 program will attempt to solve; edit code "44" displayed if not possible. Program computes significance level of test.

Notation: X_i = number of observations of X in cell i ; $i = 1, \dots, m$
 h_i = $P(\text{random observation is in cell } i)$
 H_j = $P(\text{random observation is in cell } j; j \leq i)$
 t = test statistic
 H_0 = null hypothesis
 H = hypothesized CDF of random variable X
 F = actual CDF of random variable X (unknown)
The hypothesized CDF, H , may be defined by specifying h_i or H_j values.

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS	DISPLAY
1.	Initialize: If H defined by h_i values If H defined by H_j values		E E'	0 0
2.	Specify number of cells	m	R/S	m
3.	Specify sample size	n	R/S	1
4.	Define H with either h_i values or H_j values	h_i or H_j ($i = 1, \dots, m-1$) h_m or H_m	R/S R/S	1+1 1 (note 1)
2.	Specify cell frequency counts	X_i ($i = 1, \dots, m-1$) X_m	R/S R/S	1+1 0 (note 2)
5.	Specify direction of test: If $H_0: F(x) = H(x)$ If $H_0: F(x) \geq H(x)$ If $H_0: F(x) \leq H(x)$		A B C	t t t (note 3)
6.	Enter both sides of Card 2			
7.	Compute significance level (S.L.)		A	S.L.
8.	Evaluate S.L. for two-sided test; (S.L. exact for one-sided test)		B xst C E	max S.L. min S.L. max error recall S.L.

Note 1: Edit code "22" indicates ($h_1 + \dots + h_m$) greater than 1.01 or less than .99. User may press "A" to normalize h_i 's & continue.

Note 2: Edit code "33" indicates ($X_1 + \dots + X_m$) $\neq n$. Cannot proceed.

Note 3: Edit code "44" indicates problem too large. Recall t from Reg #0.

APPENDIX D

USE OF PENDING ARITHMETIC REGISTERS IN THE TI-59

The TI-59 calculator has eight pending arithmetic registers. They are not accessible from the keyboard but are accessible from within a program and are used extensively in Discrete K-S. A detailed discussion of these special registers has been provided by a non-profit organization called the SR-52 Users Club [Ref. 10]. Unfortunately the user's manual provided by the manufacturer [Ref. 8] does not discuss them.

Each of the eight pending registers can be accessed with "82" followed by a two digit number, represented here as "mn". The access code "82" is represented as "HIR" by a Texas Instruments printer. This mnemonic has been interpreted as both "Hierarchy Internal Register" and "Hidden Internal Register".

The value of *m* determines which register operation is performed, i.e.,

<i>m</i>	operation
0	STO
1	RCL
3	SUM
4	Prd
5	INV SUM
6, 7, 8, or 9	INV Prd .

The value of *n* (1, 2, . . . , or 8) determines which HIR is

accessed. For example, to add a number directly to the value currently in HIR 4 the program codes "82, 34" would be used.

To enter a two digit code like "82" or "34" in a program it is convenient to "trick" the calculator with a register command. For instance, with the calculator in the "LRN" mode press "STO, 8, 2" then backstep (with "BST") twice and "42" (for "STO") will be displayed. Delete the register command "STO" by pressing "del" and the "82" remains as a merged code. Advance the program pointer with "SST" one step and the remaining program steps can be entered.

The pending arithmetic registers serve several purposes. When nested arithmetic operations are performed the operands are first pushed into HIR 1 and then into 2, 3, . . . , 8. Use of the Op codes 1, 2, 3, and 4 assign values to HIRs 5, 6, 7, and 8, respectively. Other keyboard operations which affect the HIRs are "P-R" and "D.MS" .

After extensive experimentation with HIRs the writer is convinced that the TI-59 uses HIRs in other ways besides those mentioned. For instance, Discrete K-S, Card 2, does not use nested arithmetic operations, "P-R", or "D.MS". It uses HIRs 2 - 7. When the program was modified to also use HIR 1 it did not perform computations correctly. For some reason the manufacturer has not disclosed any information about the HIRs except to acknowledge their existence.

Utilizing HIRs modestly increases the calculator's data storage capacity. It also provides a place to store a few

numbers to be retained after "CM" is pressed. When incorporating HIRs into a program the following approach is recommended. First, write the program without using any HIRs and validate it. Second, incorporate the desired HIRs to free regular data registers and then revalidate the program. Trying to find an error in a program that was written with HIRs initially can be very frustrating; the program may be affected by some mysterious HIR-related problem that the user may never find.

LIST OF REFERENCES

1. Dixon, W.J. and Massey, F.J., Introduction to Statistical Analysis, 3d ed., McGraw-Hill, 1969.
2. Kolmogorov, A., "Sulla Determinazione Empirica di una Legge di Distribuzione," Giornale dell'Istituto Italiano degli Attuari, v. 4, p. 83-91, 1933.
3. Smirnov, N., "Table for Estimating the Goodness-of-Fit of Empirical Distributions," Annals of Mathematical Statistics, v. 19, p. 279, 1948.
4. Bradley, J.V., Distribution-Free Statistical Analysis, Prentice Hall, 1968.
5. Conover, W.J., "A Kolmogorov Goodness-of-Fit Test for Discontinuous Distributions," Journal of the American Statistical Association, v. 67, no. 339, p.591, September 1972.
6. Mood, A.M., Graybill, F.A., and Boes, D.C., Introduction to the Theory of Statistics, 3d ed., McGraw-Hill, 1974.
7. Birnbaum, Z.V. and Tingey, F.H., "One-Sided Confidence Contours for Probability Distribution Functions," Annals of Mathematical Statistics, v. 22, p. 592, 1951.
8. Texas Instruments, Personal Programming, 1977.
9. Allen, M.E., Kolmogorov-Smirnov Tests for Discrete Distributions, M.S. Thesis, Naval Postgraduate School, 1976.
10. SR-52 Users Club, 52-Notes, v. 2, no. 9, September 1977.

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